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PROJECT APOLLO

ATTENUATION OF CORPUSCULAR RADIATION THROUGH SHIELDING

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

SPACE TASK GROUP

Langley Air Force Base, Va.

August 24, 1961

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ATTENUATION OF CORPUSCULAR RADIATION THROUGH SHIELDING

SUMMARY

A survey has been made of the methods of calculating the attenuation of radiation in matter. This presentation includes information on the range of protons and electrons considering both ionization energy loss and the formation of secondary radiation.

INTRODUCTION

The radiation hazards faced by manned space vehicles demand that consideration be given to the protection of the crew. To evaluate shielding requirements or techniques, it is necessary to understand the behavior of corpuscular radiation in its passage through matter. The purpose of this paper is to summarize the theories of attenuation of particles in matter and the creation of secondary radiation. Consideration will be given to the behavior of the proton and the electron as primary particles. The secondary radiation problem will deal only with the formation of X-rays and γ-rays from electron Bremmstrahlung and the formation of neutrons by proton interaction.

SYMBOLS

A	atomic weight of the material in which the interactions take place
c	velocity of light
E	kinetic energy
Ep	kinetic energy of bombarding particle
E'	kinetic energy acquired by an atomic electron
h	Plank's constant five-structure constant 1/137.038
I (Z)	ionization potential of atoms in shielding material approximately 12.5 Z electron volts

k col (E)	energy lost per gram $\overline{cm}^2$ in collisions with atomic electrons = $-\left(\frac{dE}{dx}\right)$ col
m	mass of particle
m_c	mass of electron
N	Avogadro number electronic charge
p	momentum $p = m\ v/\sqrt{1 - \beta^z}$
R	range of particle in any material
R_o	range of particle in some known material
r_e	classical radius of the electron
U	total energy $U = E + mc^2$
Z	atomic number of the material in which the interactions take place
z	atomic number of the bombarding particle
β	velocity of particle relative to the velocity of light $\beta = \lvert pc \rvert / U$
ρ	density of material
ν	velocity of particles
$(\sigma N/A)\ dx$	probability of occurrence of a process in a material with cross section σ in thickness, dx
$\frac{\partial\sigma(col)\ dE'}{\partial E'}$	collision or ionization cross section for shielding material
$\frac{\partial\sigma(rad)\ dE'}{\partial E'}$	radiation cross section from production of secondaries in shielding material

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DISCUSSION

Charged particles lose energy in their passage through matter mainly by two mechanisms:

(a) Ionization or collision

(b) Emission of secondary radiation

The ionization mechanism is essentially an energy loss by collision with the atomic electrons. If the incident radiation is X-rays, another process called "scattering" may take place. In this process, the atomic electrons are set in vibration by the incident X-rays and radiate secondary X-rays at a frequency characteristic of the element bombarded.

Energy loss by secondary emission can be a consequence of the direct interaction of the incident particle with the atomic nucleus or the field of the nucleus.

Thus an analysis of shielding requirements for manned space vehicles must first consider the range of the primary particle in the material, and secondly the additional problem of any secondary particle which may be formed and serve to increase the flux in the interior of a vehicle.

In order to determine this information, a knowledge of certain basic parameters is necessary; for example, cross sections for various particles and absorption coefficients for various materials.

Cross Sections for the Collision of Charged Particles with Atomic Electrons (Ionization Loss)

An important consideration in obtaining the energy loss by ionization is the evaluation of the cross section of various atoms for a particular particle. The term "cross section" actually means the cross-section area, but most frequently it is a measure of probability of an interaction taking place. The following equation from reference 1 is an example of the cross section as a measure of probability for the collision of charged particles with atomic electrons (knock-on probabilities). Let E be the energy of the incident particle and E' be the energy acquired by an atomic electron. If:

$$E' \ll E'_{max} = \frac{2\ m_e\ p^2\ c^4}{me^2c^4 + m^2c^4\ 2m_ec^2\ \left(\rho^2c^2 + m^2c^4\right)\frac{1}{2}}$$

Then the collision cross section

$$\frac{\partial\sigma(col)\ dE'}{\partial E'}\text{is:}$$

$$\frac{\partial\sigma(col)\ dE'}{\partial E'} = \frac{2Zz^2\pi r_e{}^2\ \ m_ec^2dE'}{\beta^2\ \left(E'\right)^2}$$

This is the Rutherford formula and is valid for all particles where $E' \ll E'_{max}$.

At larger values of E', the spin of the bombarding particle becomes important and we have for:

Particles of mass m and spin 0;

$$\left(\frac{\partial\sigma}{\partial E'}\right) = \left(\frac{\partial\sigma}{\partial E'}\right)\text{Rutherford}\ \left(1 - \beta^2\frac{E'}{E'_{max}}\right)$$

For particles (not electrons) of mass m and spin $\frac{1}{2}$

$$\frac{\partial\sigma}{\partial E'} = \left(\frac{\partial\sigma}{\partial E'}\right)\text{Rutherford} \times \left[1 - \beta^2\frac{E'}{E'_{max}} + \frac{1}{2}\left(\frac{E'}{E+mc^2}\right)^2\right]$$

Energy Loss by Ionization in Matter

(Ref. 2)

If $k_{col}(E) = -\left(dE/dx\right)_{col}$ is the energy lost per g/cm^2 of material in collisions with atomic electrons then for:

Protons:

$$k_{col}(E) = \frac{4Nz^2(Z/A)\pi r_e^2 \, m_e c^2}{\beta^2} \ln \frac{2m_e c^2 \beta^2}{\left(1-\beta^2\right) \; I(Z)} - \beta^2$$

Electrons: $(\beta \approx 1)$

$$k_{col} = 4N \frac{Z}{A} \pi r_e^2 \, m_e c^2 \; \ln \frac{\pi \, m_e c^2}{\left(1-\beta^2\right)^{\frac{3}{4}} I(Z)} - \frac{a}{2}$$

Cross Sections for Heavier Particles

The cross sections for heavier particles with mass m, spin $\frac{1}{2}$, and normal magnetic moment is given by:

$$\frac{\partial\sigma(rad)\; dE'}{\partial E'} = 4\alpha Z^2 \, r_e^2 \left(\frac{m_e}{m}\right)^2 \frac{dE'}{E'} \int (U, \; \nu)$$

Where

$$\int (U, \; \nu) = \left[1 + (1-\nu)^2 - \frac{2}{3}(1-\nu)\right] \left[\ln \frac{2U}{mc^2} \quad \frac{h}{\left(mc \; 0.49 r_e A^{\frac{1}{3}}\right)} \frac{1-\nu}{\nu}\right] - \frac{1}{2}$$

The effects of the nuclear radius have been included. The effects of the atomic electrons have not been included.

Range of Electrons $\left(B^-\right)$ and Protons $\left(H^+\right)$

in Matter Considering Only Collision Energy Loss

The range of the electron has been determined for several materials and is given in figure 1 (ref. 2). For most materials, the following empirical relationship is accurate to ±5 percent, in the energy range, 5 Mev to 3 Mev (ref. 3).

$$R_{exp}\left(g/cm^2\right) = 0.52E - 0.09$$

R_o = range of the electron in a known material

E = energy in Mev

Reference 3 suggests that the range of heavy particles where energy loss is mainly by ionization is approximately the same distance in matter before being stopped and that this distance is:

$$R\ (E) = \int_{E_{\text{experimental}}}^{E} \frac{dE}{k_{col}\ (E')} + R_{exp}$$

Where R_{exp} is the observed range for some known energy E_{exp}.

For a given material

$$k_{col} = z^2 f\ (\beta) \quad \beta = f\left(E/_m\right)$$

$$R = \frac{m}{z^2}\ f\left(E/_m\right) = m/_{z}{}^{2} f\left(p/_m\right)$$

A more useful empirical relationship is found in reference 2.

$$\frac{R_{T_{exp}}}{R_o} = \frac{\rho_o}{\rho T_{exp}} \sqrt{\frac{A_{T_{exp}}}{A_o}}$$

Where R_o p_o A_o are the range density and atomic weight for a known substance (usually air is used). Figures 2 and 3 illustrate the effective range of protons for several materials.

Energy Loss of Electrons by Emission of Radiation

The slowing down of electrons in matter can be a source of secondary X-rays. Roughly the ratio of energy lost by radiation to energy lost by ionization is given by the following equation:

$$\frac{dE/dx \ (rad)}{dE/dx \ (ion)} = \frac{Z\ E}{800}$$

Where E equals the electron energy in Mev and Z equals the atomic number of the material.

If the energy of the particle is known, the quantity of X-rays, W, can be calculated directly from the following:

$$W = \frac{1.98 \times 10^{-4} \ (1.98\ E + 2)\ Z}{1 + 0.35 \log_{10}\left(\frac{82}{Z}\right)}$$

Cross Sections for the Loss of Energy

From a Charged Particle by Emission of Radiation (ref. 2)

Electron Cross Sections.- The cross section for emission of a proton of energy E, when an electron of kinetic energy E and a total energy U interacts with an atom, is effected by a number of factors. To a great extent the effect of electrostatic field shielding of the nucleus by atomic electrons determines the cross section. The parameter γ is a measure of this shielding, if $\gamma \gg 1$ shielding is neglected, if $\gamma \ll 1$ shielding is considered complete. In cases where $U \gg 137\ m_e c^2\ Z^{-\frac{1}{3}}$ then complete screening is always present.

The cross section for $U \gg m_e c^2$

$$\frac{\partial\sigma(\mathrm{rad})\ dE}{\partial E'} = 4\alpha Z\ (Z + 1)\ r_e{}^2\ \frac{dE'}{E'}\ f\ (U,\ \nu)$$

where $V = \frac{E'}{U}$ and $\int (U,\ \nu)$ is:

$$\int (U,\ \nu)\ \gamma \gg 1\ = \left[1 + (1-\nu)^2\ \frac{2}{3}\ (1-\nu)\right] \left[\ln\left(\frac{2}{m_e c^2}\right) \cdot\ \frac{1-\nu}{\nu} - \frac{1}{2}\right]$$

$$\int (U,\ \nu)\ \gamma \approx 0 \left[1 + (1-\nu)^2 - \frac{2}{3}\ (1-\nu)\right] \left[\ln 183\ Z^{-\frac{1}{3}}\ \right] + \frac{1}{9}\ (1-\nu)$$

Experimental evidence with 62 Mev particles has shown these values to be high and indicate that the cross-section value should be divided by:

$$1 + 0.12\left(\frac{Z}{82}\right)^2$$

Energy Loss of Protons

by Emission of Radiation

There is very little available information on the production of secondaries by proton interaction. The main interest in this area is the possible production of neutrons (σ_{η}') and gamma-rays (γ). According to reference 3, the creation of gamma-rays does not appear to be a problem for short-term missions. This reference published a graph obtained from the University of California Radiation Laboratory indicating the neutron flux from bombardment of a thick copper target with fast protons. This information is given in figure 4.

CONCLUDING REMARKS

The attenuation of corpuscular radiation is accomplished mainly by two mechanisms in matter, ionization, and the production of secondary radiation. Ionization accounts for the greatest attenuation in the majority of instances. The production of secondaries can be minimized generally by the choice of low Z number materials.

In order to assign definite values to shielding requirements, it is necessary to have accurate cross-section data for each process. There is a scarcity of such information for the particles of interest for analysis of shielding requirements.

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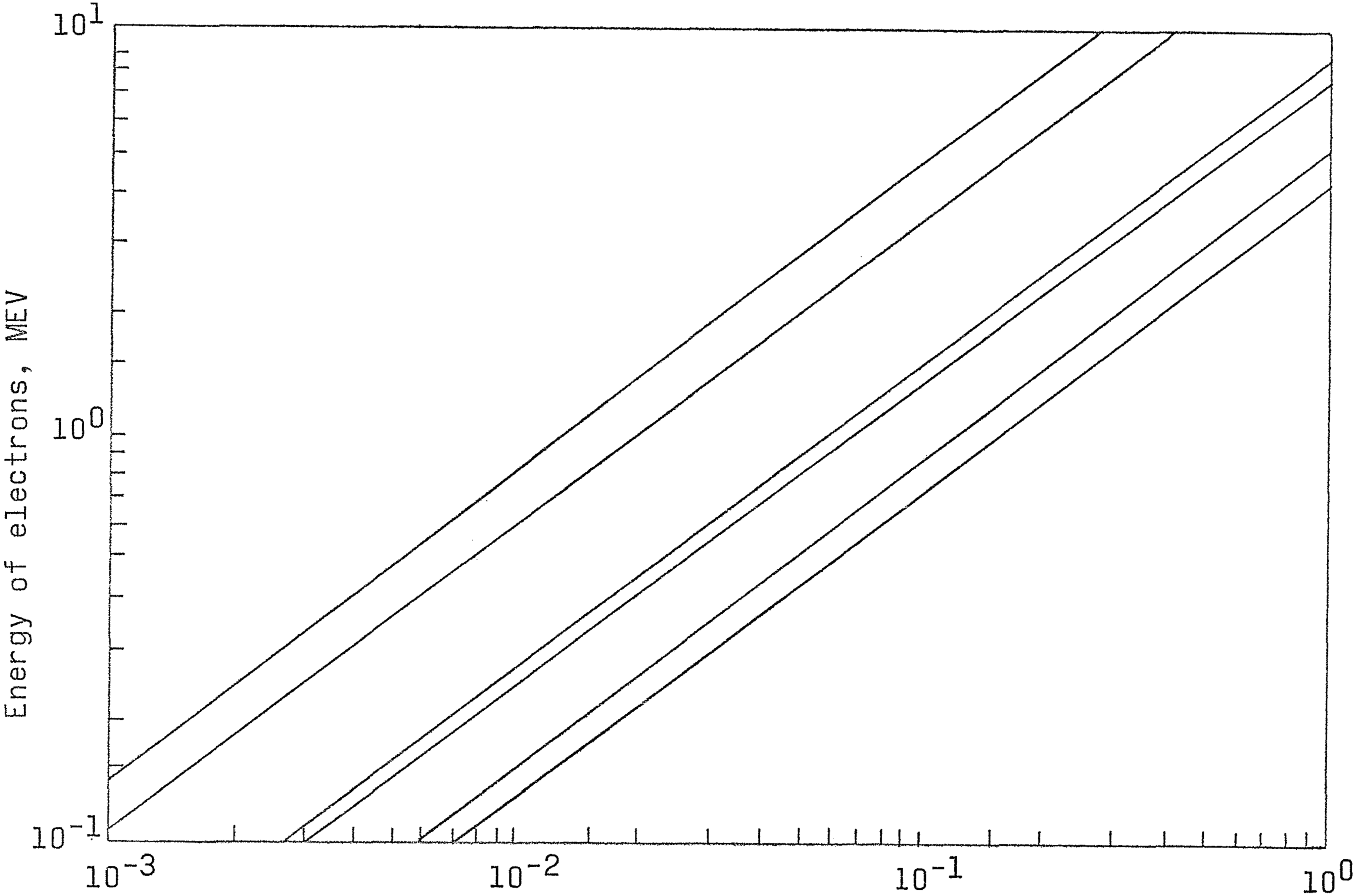

Figure 1.- Maximum range of electrons, in.

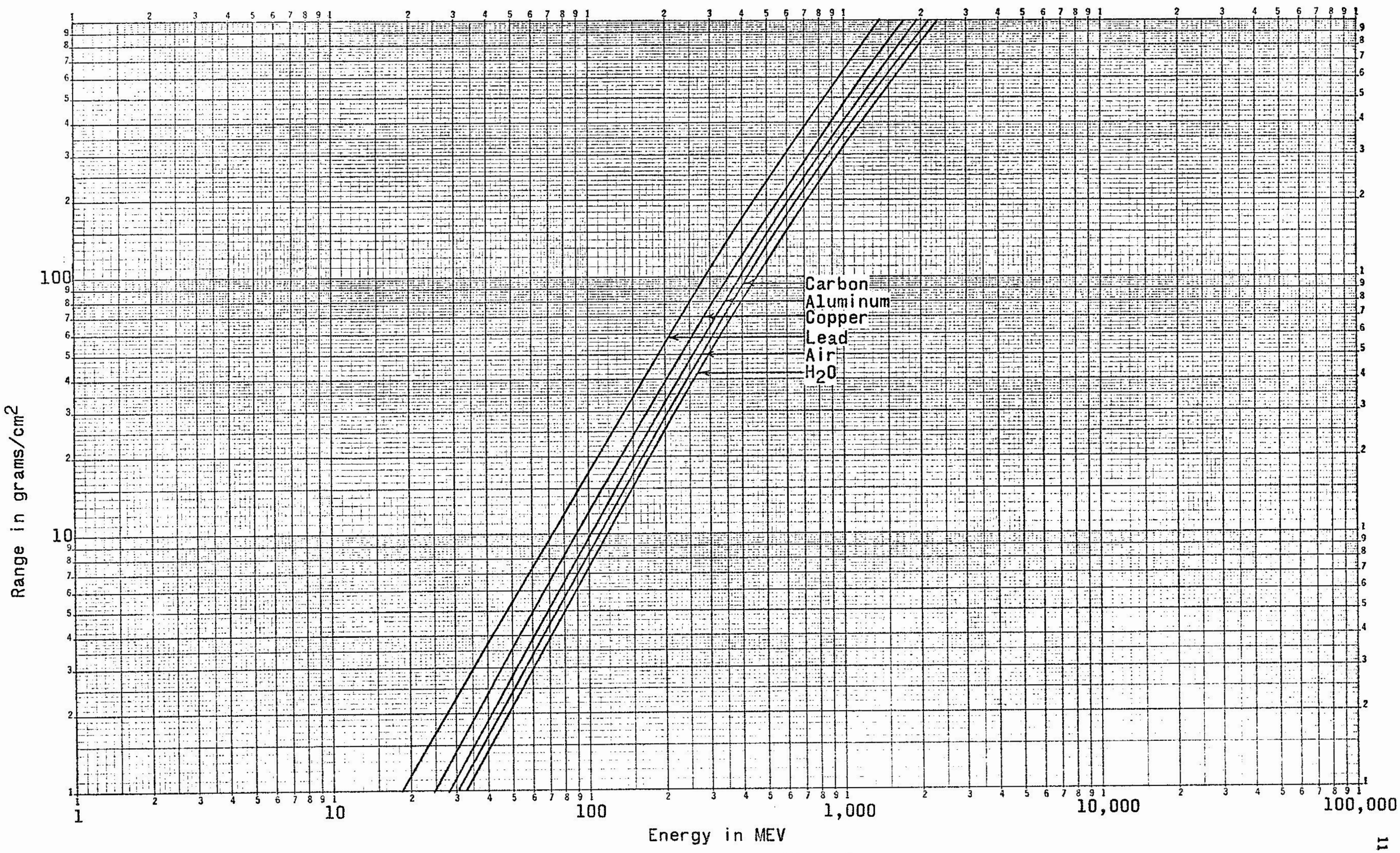

Figure 2.- Range energy relations for protons.

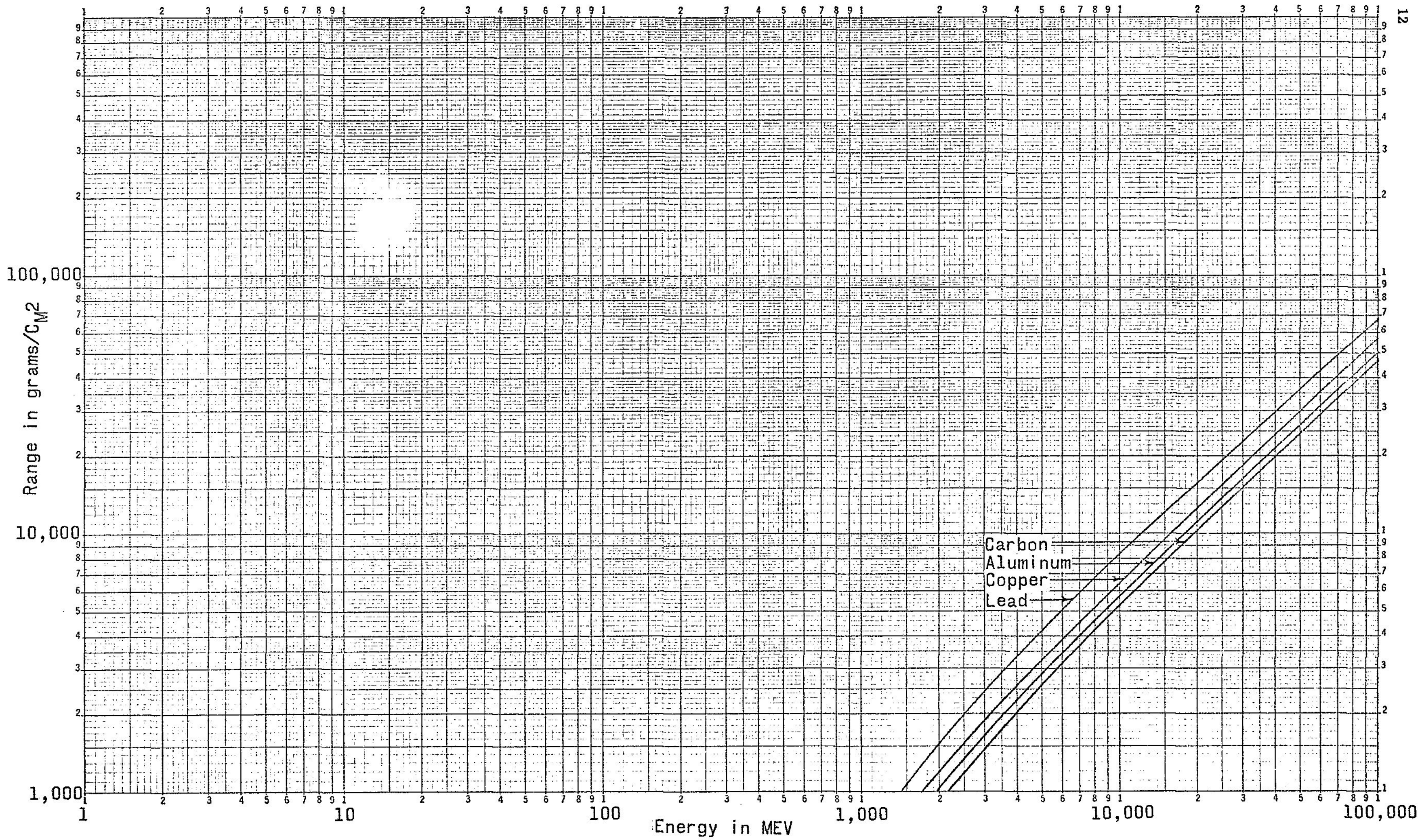

Figure 3.- Range energy relations for protons.

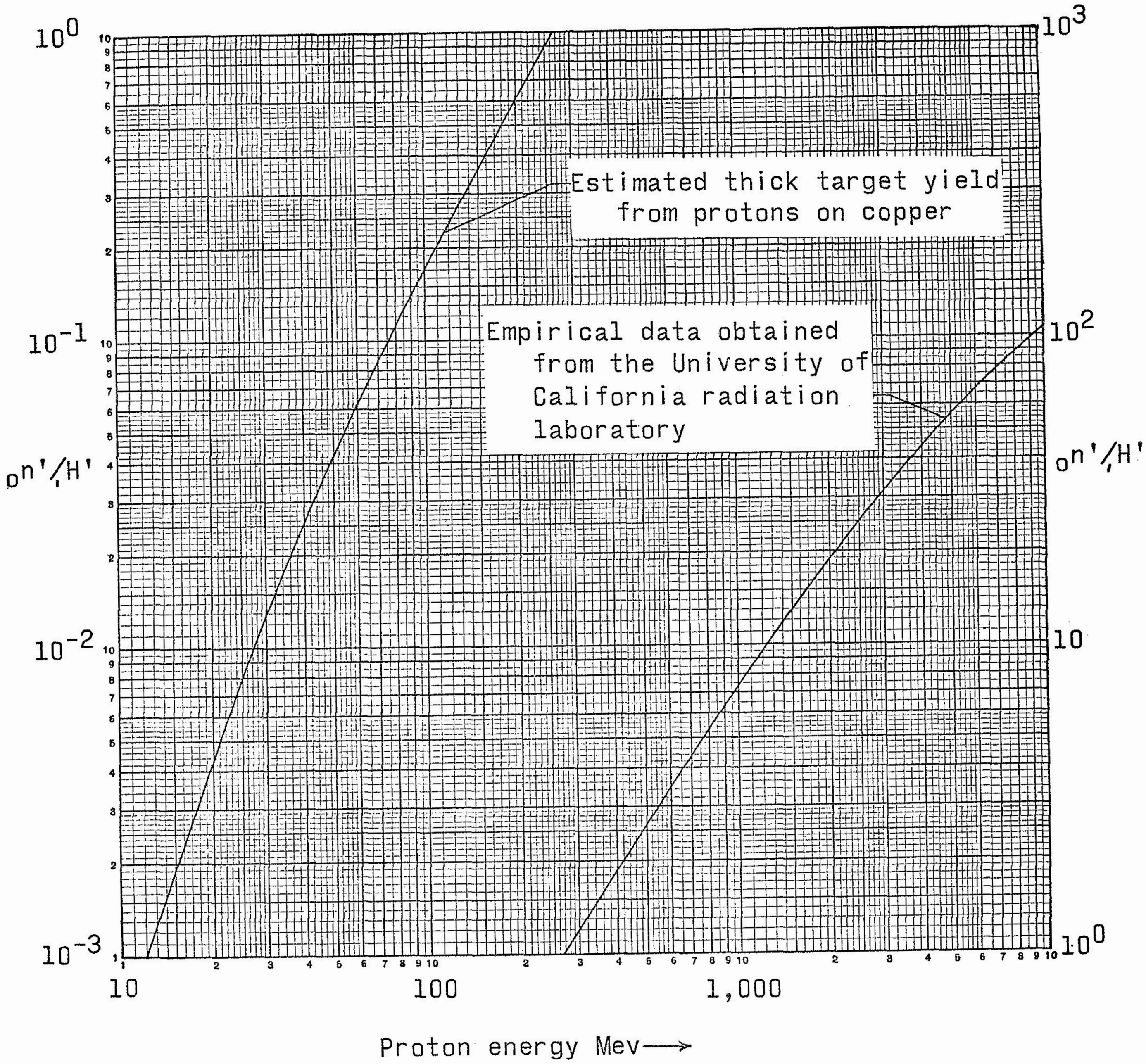

Figure 4.- Neutron yield from proton interaction with copper.